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Title: LUNA Condition Based Monitoring Update: Mahalanobis distance for Individual Damage Types

Author(s): Green, Andre Walter

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LUNA Condition Based Monitoring Update:
Mahalanobis distance for Individual Damage Types

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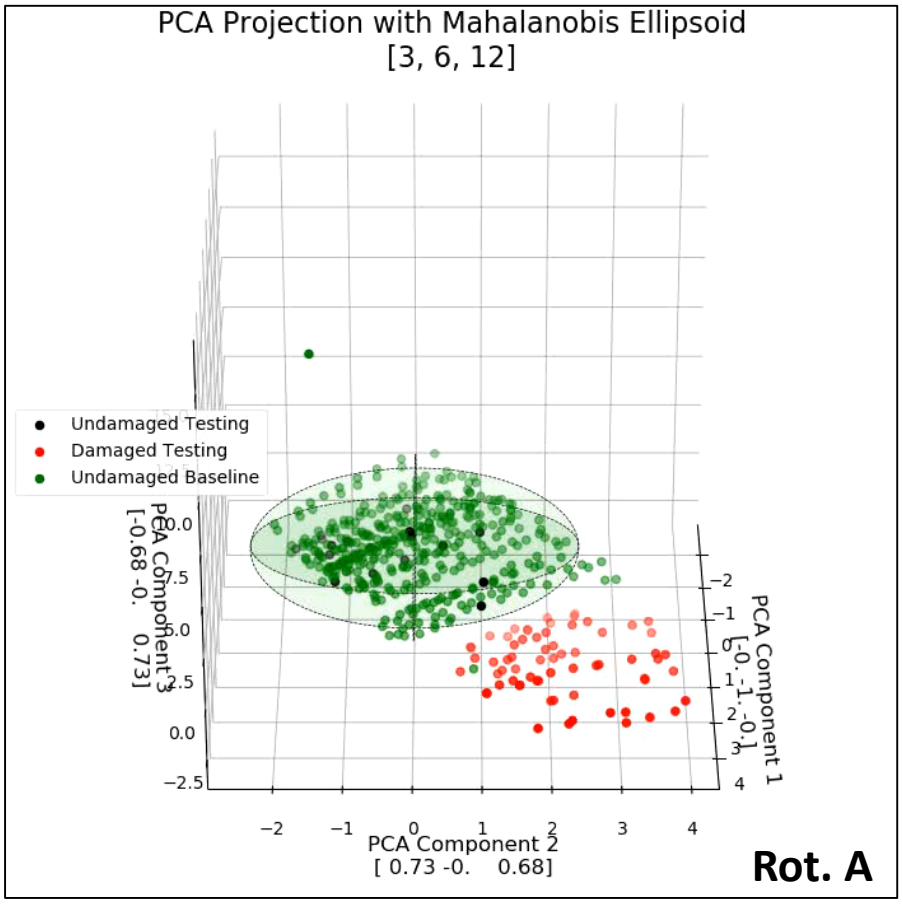
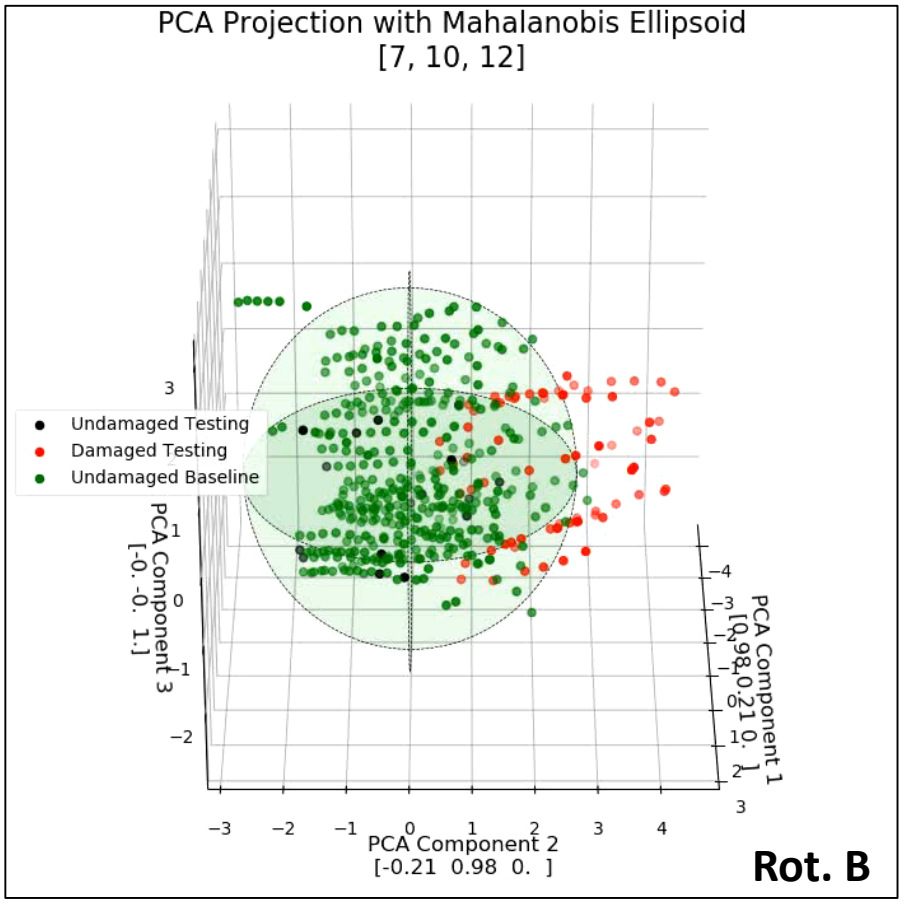
Andre’ Green

The data in the following slides comes from the multi-actuation time dataset with recordings after 25K, 51.4K, and 101K actuations.

For visualization, only 3 features (best of a subset-selection) are used.

ELoad vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]





------- ELoad --------- [ROT. A]

Subset [5, 6, 10] for [ELoad]:min: 95.12% | max: 100.0% | median: 99.19% | mean: 98.74%

Subset [3, 6, 12] for [ELoad]:min: 98.37% | max: 100.0% | median: 99.19% | mean: 99.37%

Subset [9, 10, 12] for [ELoad]:min: 96.75% | max: 100.0% | median: 100.0% | mean: 98.92%

99.37%
[Mean]

------- ELoad --------- [ROT. B]

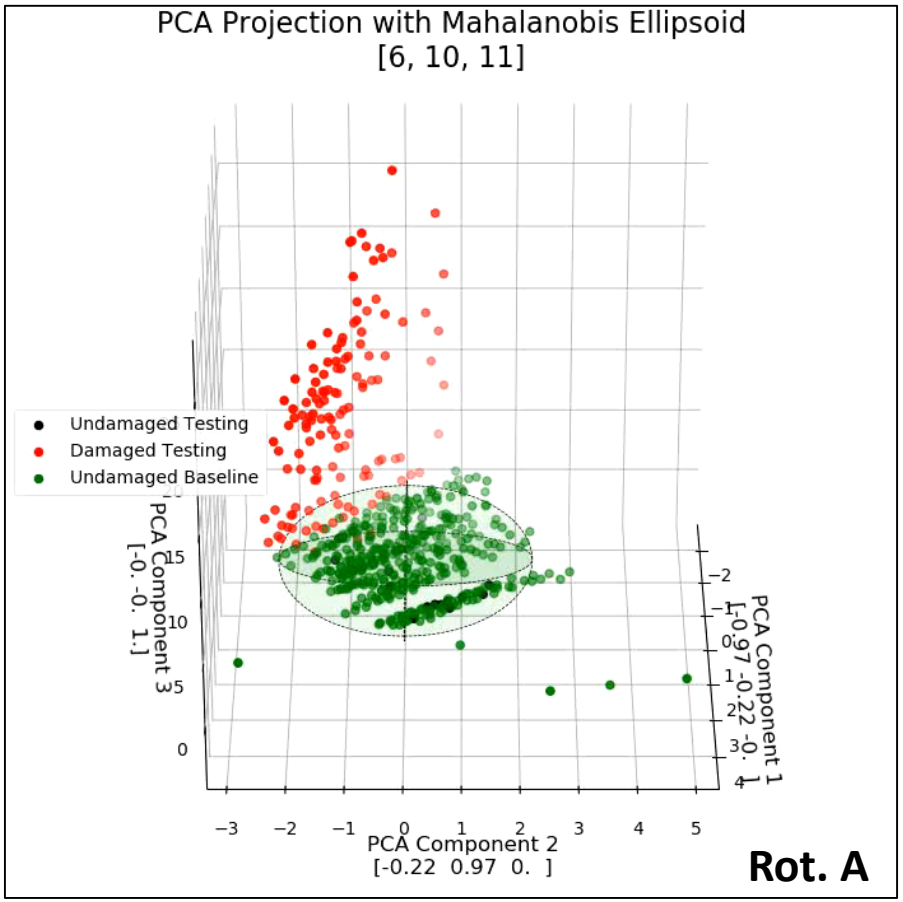
Subset [5, 6, 10] for [ELoad]:min: 98.39% | max: 100.0% | median: 99.2% | mean: 99.28%

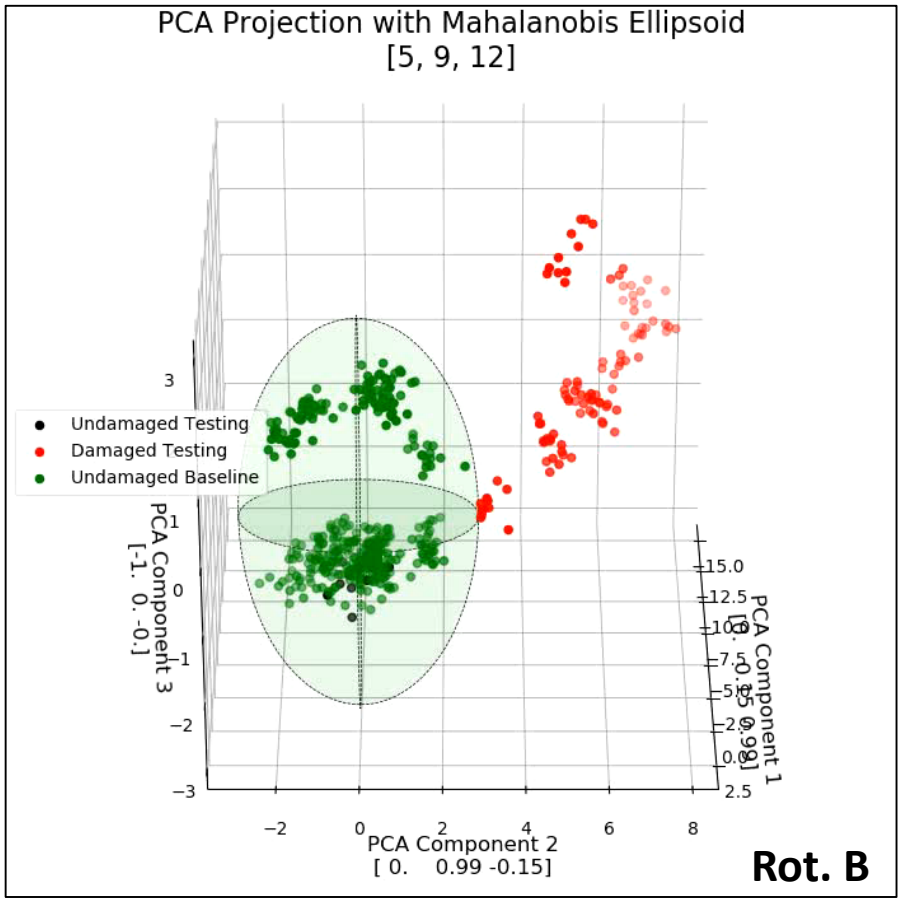
Subset [7, 10, 12] for [ELoad]:min: 97.58% | max: 100.0% | median: 100.0% | mean: 99.46%

Subset [5, 6, 12] for [ELoad]:min: 96.77% | max: 100.0% | median: 100.0% | mean: 99.02%

99.46%
[Mean]

ELeak vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]





------- ELeak --------- [ROT. A]

Subset [7, 11, 12] for [ELeak]:min: 93.01% | max: 97.31% | median: 96.24% | mean: 95.69%

Subset [6, 11, 12] for [ELeak]:min: 89.25% | max: 97.85% | median: 96.76% | mean: 94.92%

Subset [6, 10, 11] for [ELeak]:min: 90.86% | max: 98.39% | median: 97.3% | mean: 95.99%

95.99%
[Mean]

------- ELeak --------- [ROT. B]

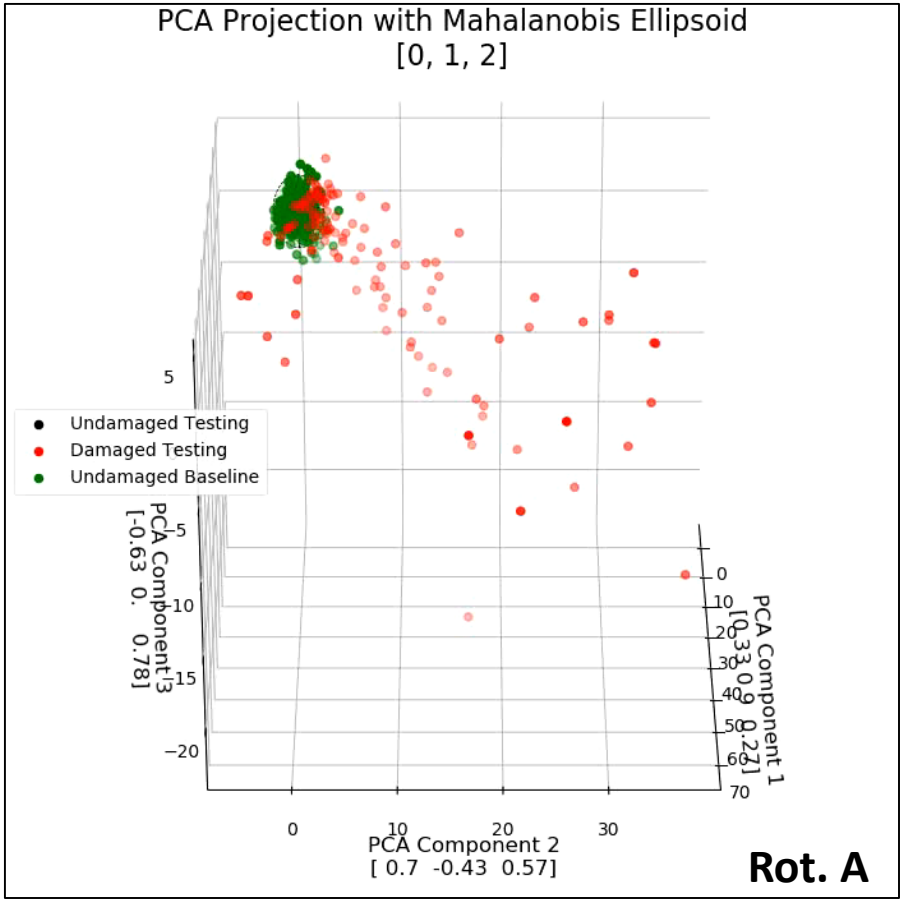
Subset [5, 9, 12] for [ELeak]:min: 99.47% | max: 100.0% | median: 100.0% | mean: 99.82%

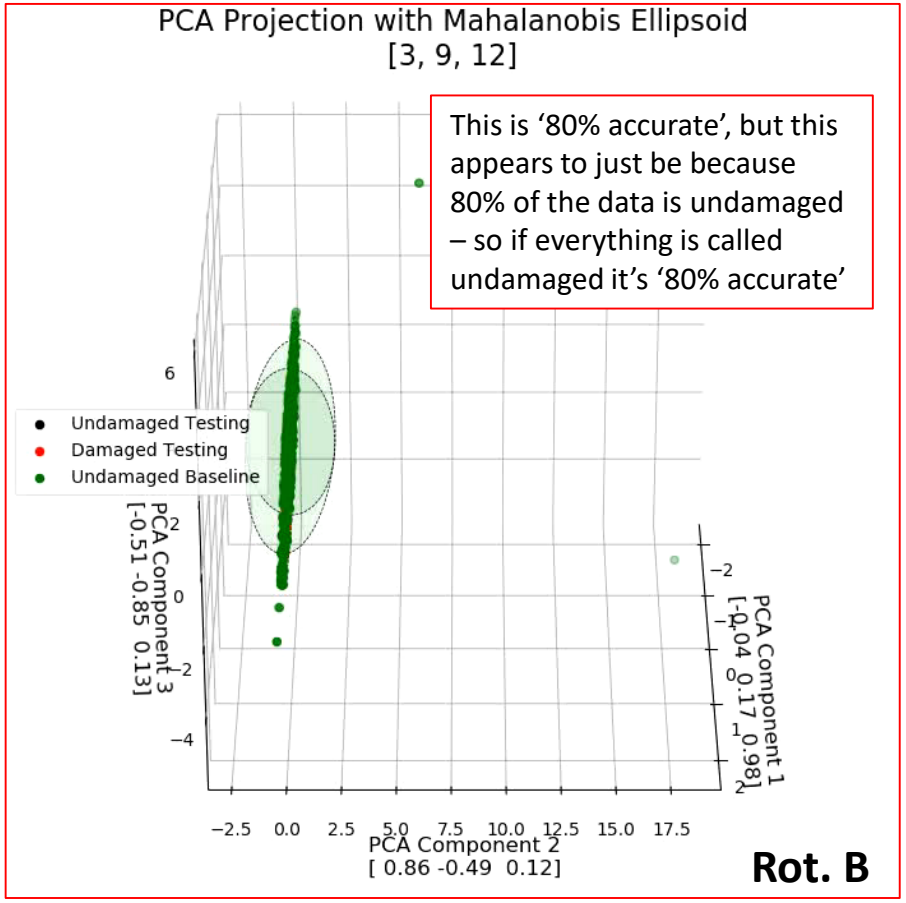
Subset [9, 11, 12] for [ELeak]:min: 96.83% | max: 100.0% | median: 100.0% | mean: 99.53%

Subset [10, 11, 12] for [ELeak]:min: 98.41% | max: 100.0% | median: 100.0% | mean: 99.65%

99.82%
[Mean]

FBrake vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]





------- FBrake --------- [ROT. A]

Subset [0, 2, 4] for [FBrake]:min: 83.12% | max: 94.41% | median: 93.12% | mean: 91.74%

Subset [0, 2, 8] for [FBrake]:min: 84.38% | max: 96.88% | median: 93.79% | mean: 92.64%

Subset [0, 1, 2] for [FBrake]:min: 88.75% | max: 96.25% | median: 94.38% | mean: 93.68%

93.68% [Mean]

------- FBrake --------- [ROT. B]

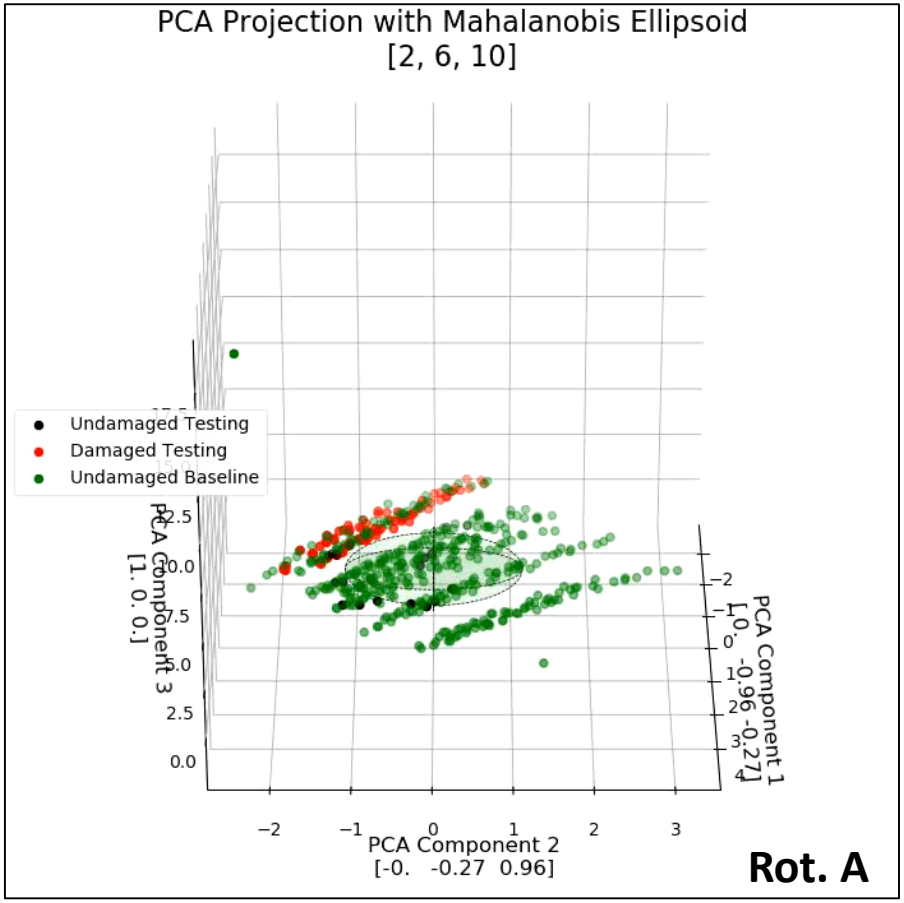
Subset [4, 6, 7] for [FBrake]:min: 49.38% | max: 83.02% | median: 81.13% | mean: 73.89%

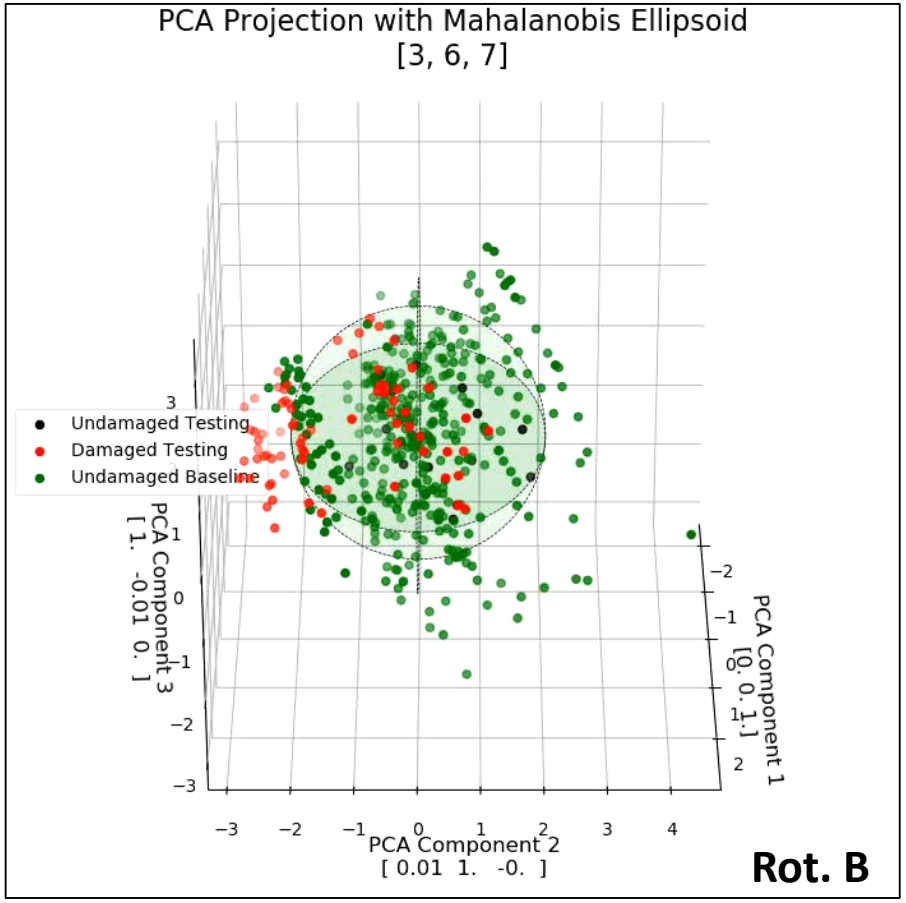
Subset [3, 7, 12] for [FBrake]:min: 59.38% | max: 84.38% | median: 82.39% | mean: 75.06%

Subset [3, 9, 12] for [FBrake]:min: 67.92% | max: 84.91% | median: 83.12% | mean: 79.3%

79.3% [Mean]

ILeak vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]





------- ILeak --------- [ROT. A]

Subset [4, 6, 12] for [ILeak]:min: 71.79% | max: 92.31% | median: 86.44% | mean: 84.65%

Subset [6, 7, 12] for [ILeak]:min: 64.96% | max: 89.83% | median: 86.44% | mean: 84.46%

Subset [2, 6, 10] for [ILeak]:min: 68.38% | max: 90.6% | median: 88.89% | mean: 84.74%

84.75%
[Mean]

------- ILeak --------- [ROT. B]

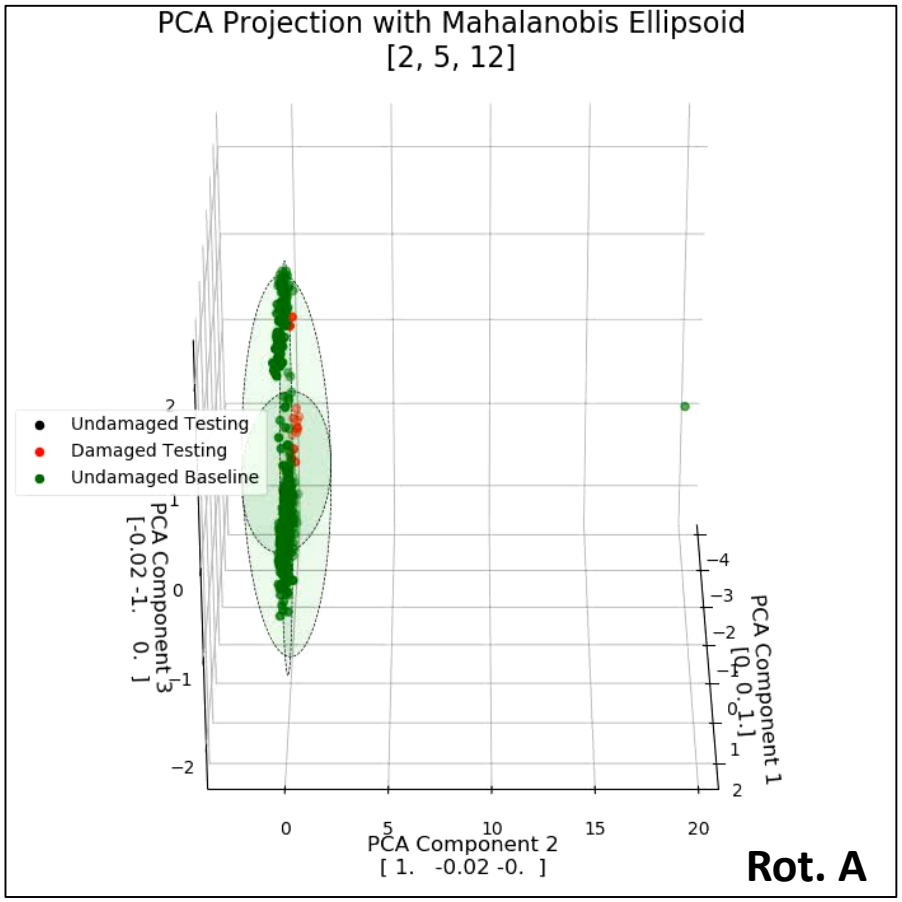
Subset [0, 7, 12] for [ILeak]:min: 83.9% | max: 93.22% | median: 89.83% | mean: 88.35%

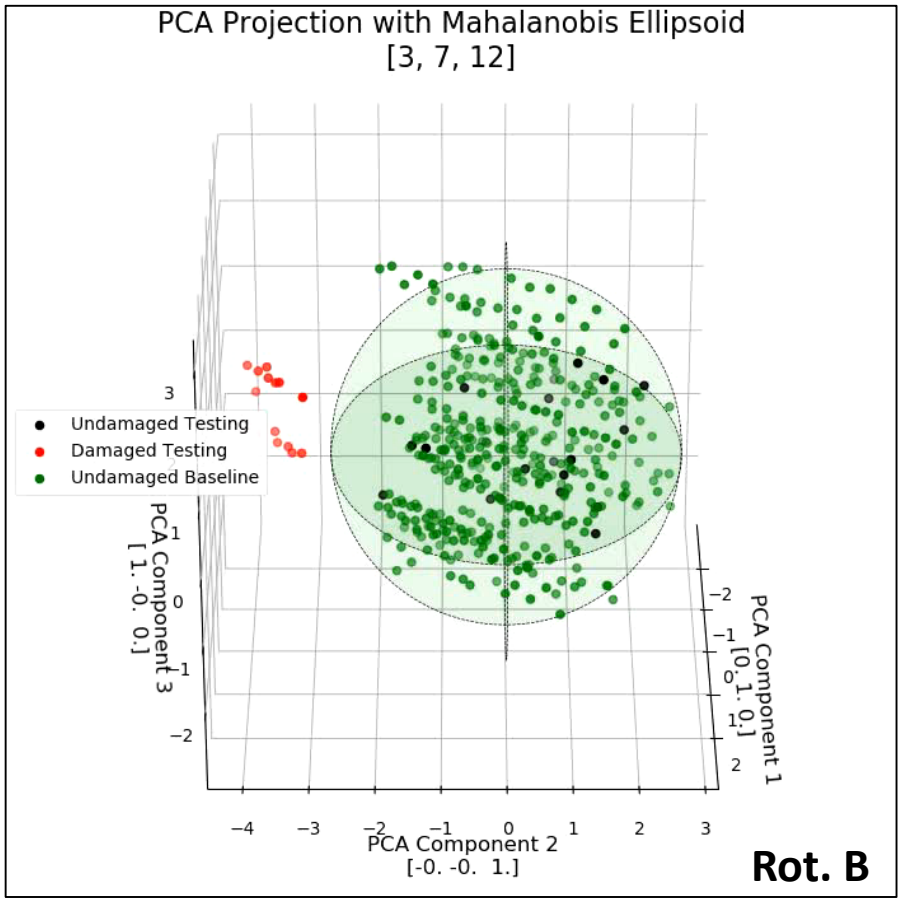
Subset [4, 10, 12] for [ILeak]:min: 69.75% | max: 94.92% | median: 90.68% | mean: 87.61%

Subset [3, 6, 7] for [ILeak]:min: 89.83% | max: 94.07% | median: 91.53% | mean: 91.63%

91.63%
[Mean]

LowP vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]





------- LowP --------- [ROT. A]

Subset [2, 5, 12] for [LowP]:min: 96.0% | max: 100.0% | median: 100.0% | mean: 99.11%

Subset [6, 7, 12] for [LowP]:min: 92.0% | max: 100.0% | median: 100.0% | mean: 97.78%

Subset [2, 6, 12] for [LowP]:min: 90.0% | max: 100.0% | median: 100.0% | mean: 98.01%

99.11%
[Mean]

------- LowP --------- [ROT. B]

Subset [4, 10, 12] for [LowP]:min: 94.12% | max: 100.0% | median: 98.04% | mean: 97.39%

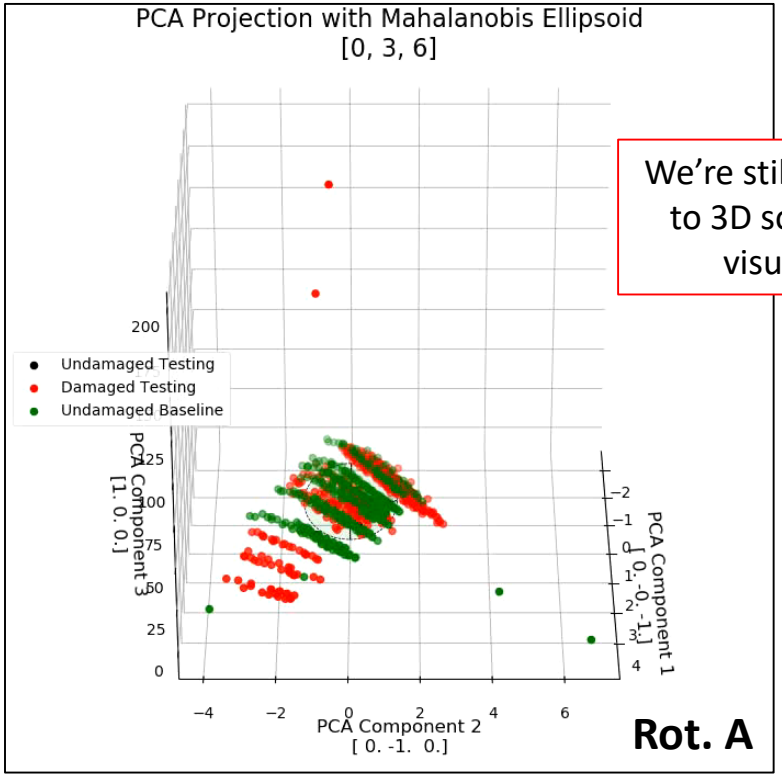
Subset [5, 7, 10] for [LowP]:min: 88.24% | max: 100.0% | median: 98.04% | mean: 96.53%

Subset [3, 7, 12] for [LowP]:min: 96.08% | max: 100.0% | median: 98.04% | mean: 97.83%

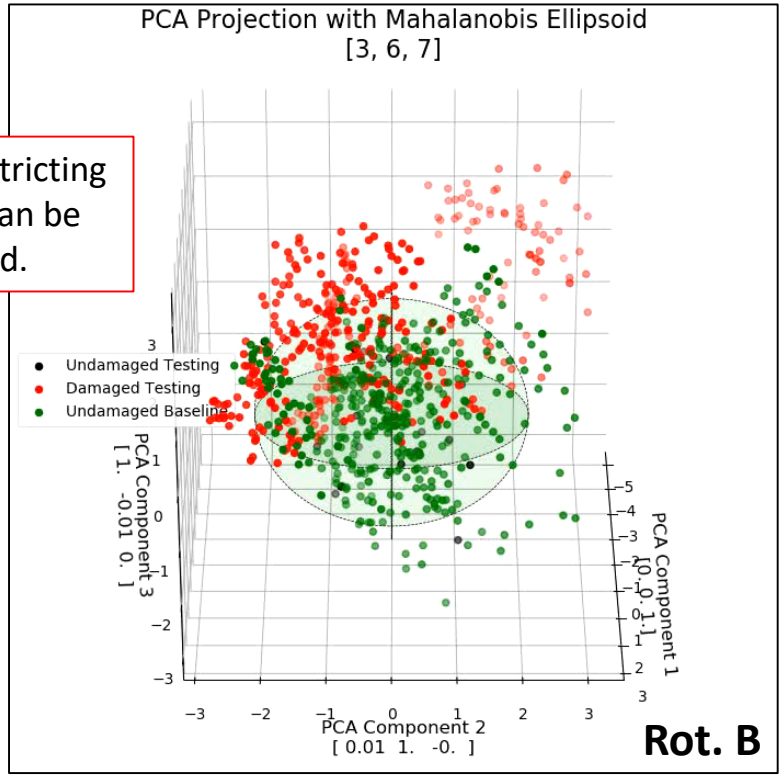
97.83%
[Mean]

All vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]

Although the aspect ratio of the Mahalanobis ellipse is the same in each of the prior figures along the corresponding dimension, (because it's always fit just to the undamaged data), its radius/scale *may be different for different* damage cases: consequently, when using all the damaged data at once, it must pick a *single* radius which works best for all.



We're still restricting to 3D so it can be visualized.



------- All_Damage_Types --------- [ROT. A]

Subset [0, 3, 6] for [All_Damage_Types]:min: 37.22% | max: 91.85% | median: 79.48% | mean: 73.36%

Subset [2, 9, 10] for [All_Damage_Types]:min: 53.33% | max: 86.85% | median: 79.67% | mean: 75.45%

Subset [4, 7, 8] for [All_Damage_Types]:min: 38.89% | max: 90.76% | median: 81.11% | mean: 77.85%

73.36% [Mean]

------- All_Damage_Types --------- [ROT. B]

Subset [3, 6, 7] for [All_Damage_Types]:min: 66.79% | max: 89.3% | median: 82.66% | mean: 79.48%

Subset [1, 5, 8] for [All_Damage_Types]:min: 36.28% | max: 91.51% | median: 84.5% | mean: 74.16%

Subset [0, 1, 2] for [All_Damage_Types]:min: 55.9% | max: 92.25% | median: 85.82% | mean: 83.48%

79.48% [Mean]

All vs. Baseline (Eload < 650) [Rot. A (>) & Rot. B (<=)]

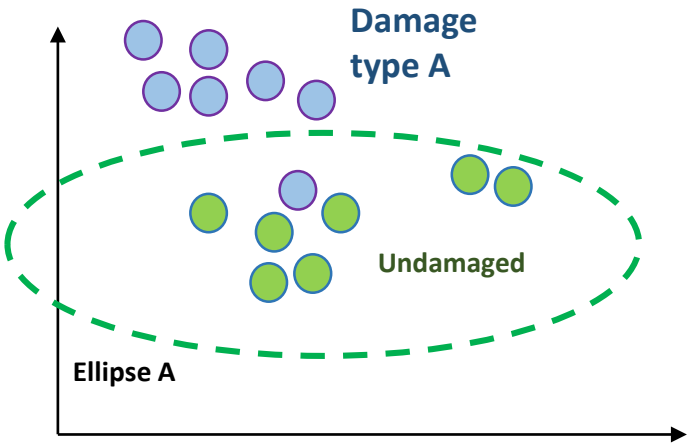
[Using all features]

[ROT. A] Subset [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] for [All_Damage_Types]:
min: 74.49% | max: 93.16% | median: 83.33% | mean: **84.19%**

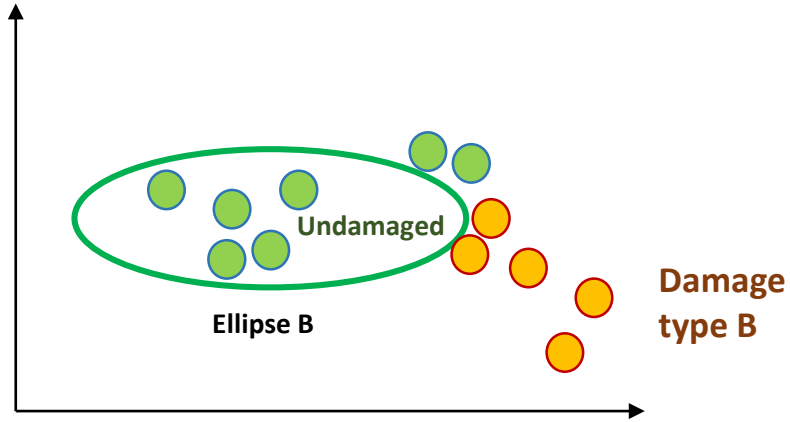
[ROT. B] Subset [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] for [All_Damage_Types]:
min: 82.84% | max: 93.36% | median: 89.67% | mean: **89.75%**

No visualizations are shown here because a 3-D down-projection of the ellipse could misleadingly show damaged points within the sphere in the projection, even though they're not actually within the 13-D sphere.

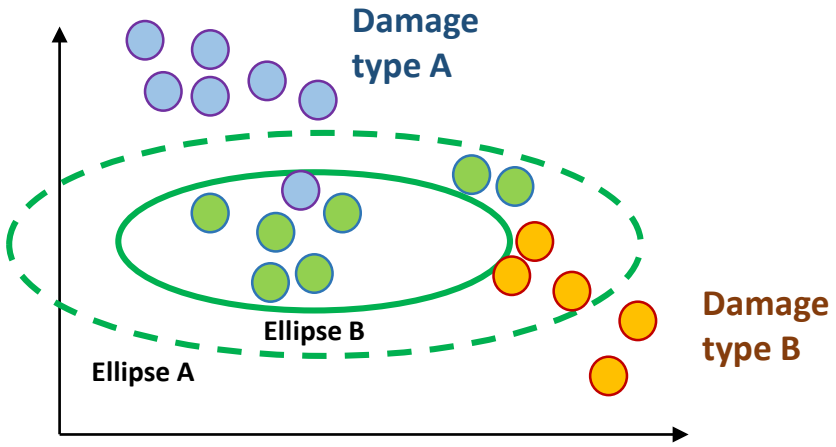
Effect of Grouping Damages Types on Accuracy



1. For damage type A, the highest-accuracy ellipse produces 1 false negative.

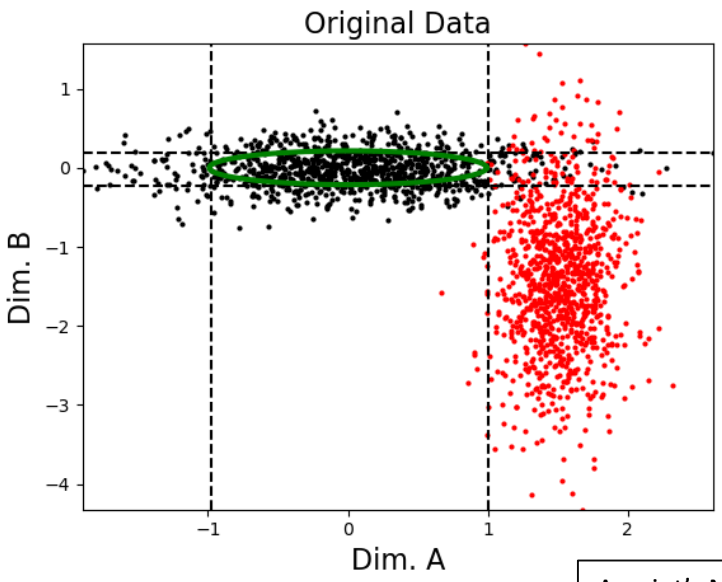


2. For damage type B, the highest-accuracy ellipse produces 2 false positives.

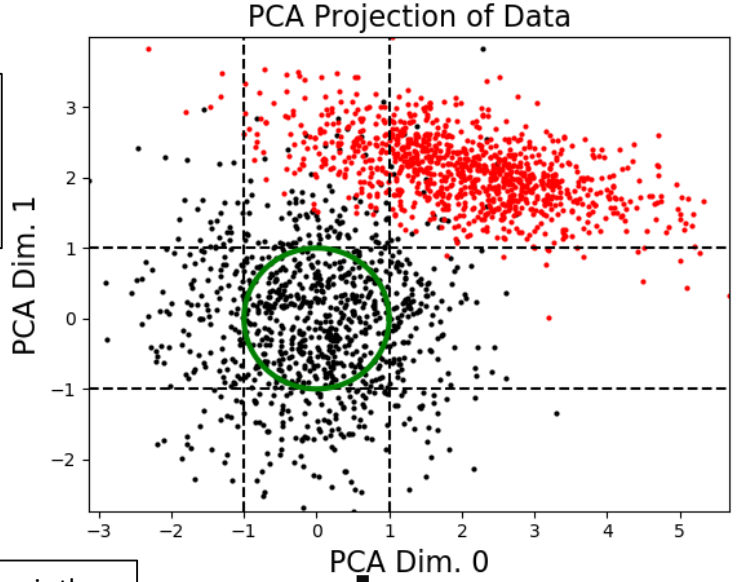


3. By picking a single radius to deal with both damage type A and B, we're stuck with either one false negative [type A] and two false positives, or four false negatives [1 type A, 3 type B].

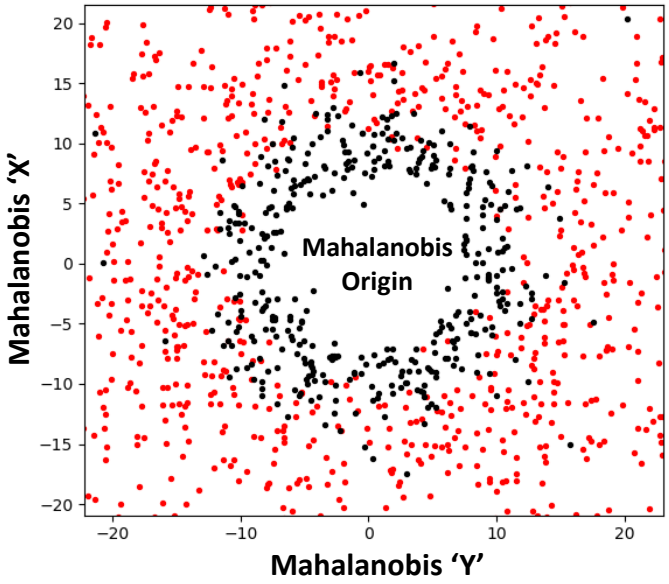
Ellipses for Histogram Separation [Illustration on generated data]



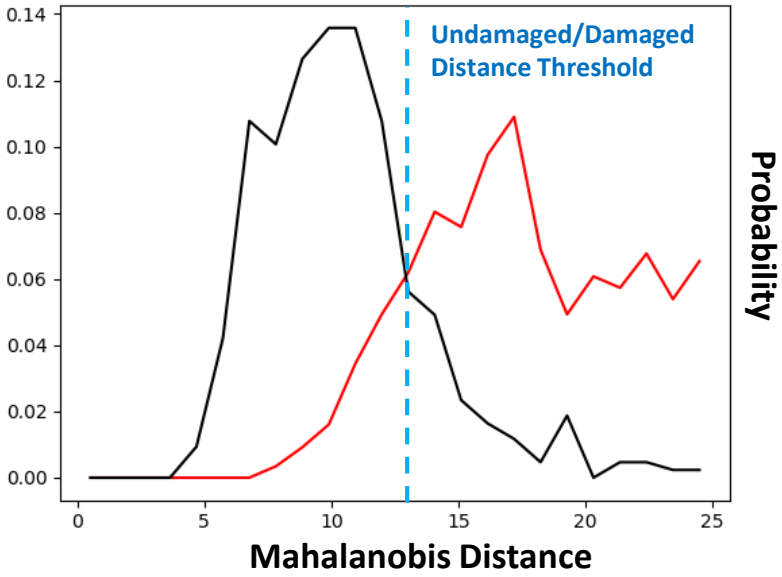
Mahalanobis /Whitening PCA Spheres the Data.



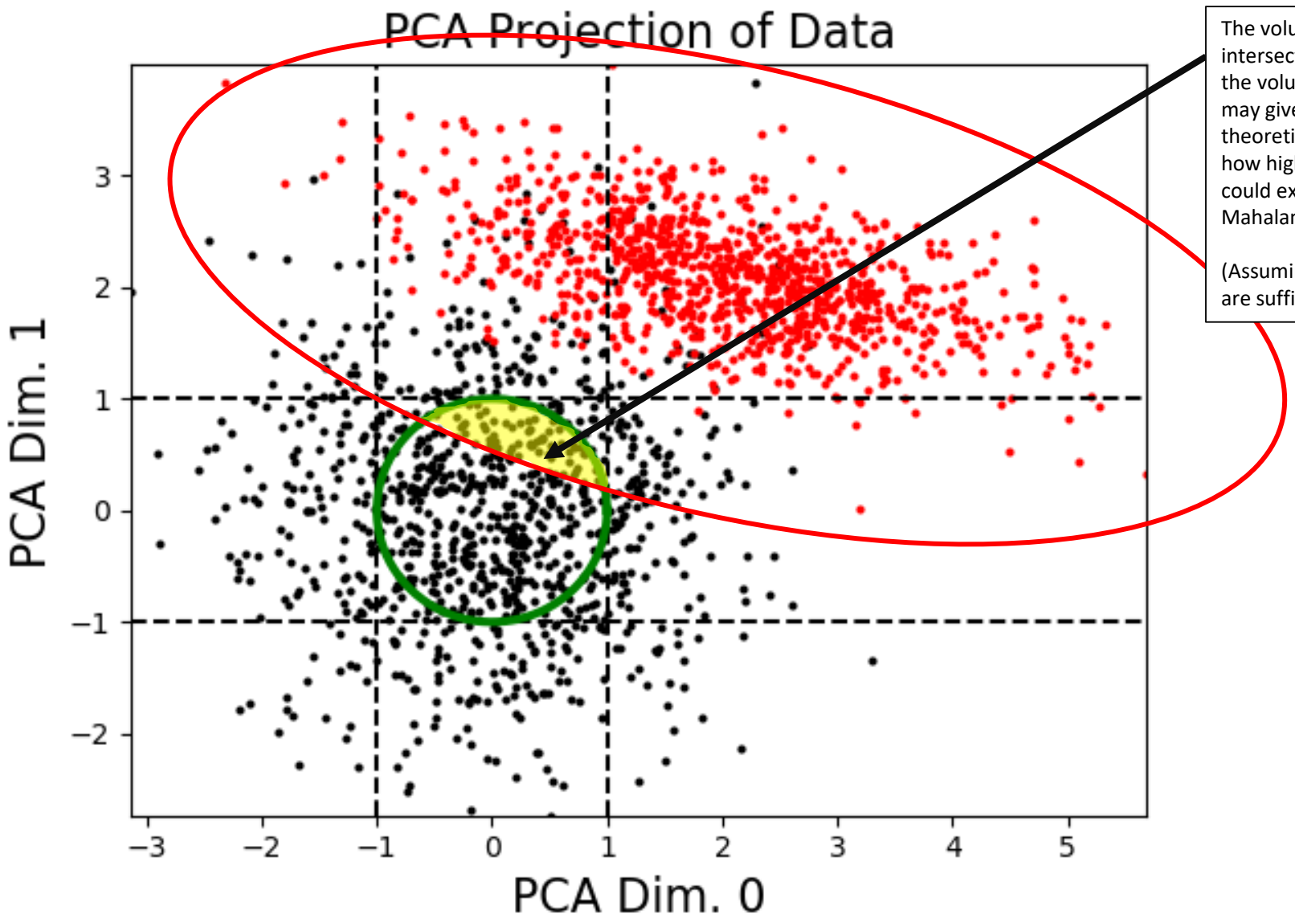
A point's Mahalanobis distance is the Euclidean distance to the origin in the transformed space



The distances can be represented with histograms – the separation of peaks determines how high the accuracy can be.



Ellipses for Histogram Separation [Illustration on generated data]



The volume of this intersection relative to the volume of the ellipses may give decent theoretical estimate of how high accuracy we could expect to get with a Mahalanobis classifier.

(Assuming the variables are sufficiently Gaussian)